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Cost and Performance Report

(EW-201349)

Central Plant Optimization for Waste Energy Reduction (CPOWER)

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Central plants contain multiple chiller, boiler, and auxiliary equipment. Each piece of equipment operates on different efficiency curves that vary with part load, ambient conditions, and other operating parameters. In addition, the site receives real-time price signals for electricity, and operators must consider fluctuating fuel prices and other costs. The system-level, dynamic optimization of central plants and distribution system implemented in this project has the potential to save energy and cost. The objective of the project was to assess the energy and economic benefits of the real-time optimization technology that commands all equipment in a central plant.

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ACRONYMS AND ABBREVIATIONS

ACS	Automation and Control Solutions (A business unit of Honeywell)
ASHRAE	American Society of Heating, Refrigeration and Air Conditioning Engineers
BACnet®	A Data Communication Protocol for Building Automation and Control Networks
BAS	Building Automation System
BMS	Building Energy Management System
BLCC	Building Life-Cycle Cost
CHP	Combined Heat and Power
CPOWER	Central Plant Optimization for Waster Energy Reduction (title of this project)
DCS	Distributed Control System
DoD	U.S. Department of Defense
DPW	Directorate of Public Works
EBI	Enterprise Buildings Integrator (a Honeywell BMS)
EO	Executive Order
ERDC-CERL	U.S. Army Engineer Research and Development Center’s Construction Engineering Research Laboratory
ESTCP	Environmental Security Technology Certification Program
FEMP	Federal Energy Management Program
FY	fiscal year
GHG	Greenhouse Gas
GPM or gpm	Gallons per minute
HBS	Honeywell Building Solutions (business unit in Honeywell ACS)
hr	hour(s)
HTS	Honeywell Technology Solutions
IAE	Integral Average Error
I/O	Input/Output
IPMVP	International Performance Measurement and Verification Protocol
LonWorks®	A networking protocol and platform for control applications
Mcf	1000 cubic feet
MMBtu	1,000,000 British thermal unit(s)
MMBH	MMBtu/hr
PO	Performance Objective

RMSE	Root Mean Squared Error
UI	User Interface

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EXECUTIVE SUMMARY

OBJECTIVES OF THE DEMONSTRATION

Central plants contain multiple chiller, boiler, and auxiliary equipment. Each piece of equipment operates on different efficiency curves that vary with part load, ambient conditions, and other operating parameters. In addition, the site receives real-time price signals for electricity, and operators must consider fluctuating fuel prices and other costs. The system-level, dynamic optimization of central plants and distribution system implemented in this project has the potential to save energy and cost. The objective of the project was to assess the energy and economic benefits of the real-time optimization technology that commands all equipment in a central plant. The performance objectives were: (1) correct optimizer performance in simulation (objective met), (2) optimizer software interconnection with plant control system (objective met), (3) 10% energy savings (objective not met), (4) preserving comfort conditions in buildings (objective met), (5) economic performance (objective not met), (6) low short cycling of equipment (objective met), and (7) effective user interface (UI) (qualitative) (objective partially met).

TECHNOLOGY DESCRIPTION

The deployed technology is a model-predictive, run-time optimization technology used to operate the generation, storage, and distribution of cooling and heating energy while maintaining building comfort. Based on the inputs of upcoming loads, price signals, central plant performance models, and building response, a mixed-integer evolutionary optimizer algorithm solves the schedules and setpoints for the major and auxiliary equipment in the central plant. The central plant model is configured from a library containing models of chillers, boilers, cooling towers, pumps, and thermal storage system. A dynamic building model mathematically represents the changes in comfort conditions in the building in response to changes in energy supplied with the distributed chilled or hot water. The models are set up based on historical data and updated as new data become available. The optimal control commands are communicated to lower level controllers that operate the equipment in the central plant. Feedback from the buildings provides corrections to the long-term forecast load; this feedback is used to adjust supplied energy.

The demonstration was designed to collect data about the original control and the optimized control, alternately. A software switch incorporated in the optimizer enabled the optimizer to run the plant or switch to the original control operation to ensure similar occupancy and functions for the buildings served by the central plant. Operational electricity and gas consumption data from all equipment were collected in the optimizer’s database for analysis.

DEMONSTRATION RESULTS

A simulation system and models of the central plants and loads to test the optimizer software in simulation. The simulation software was connected with the optimizer software using OPC server protocol. We ran several simulations with the setup to test and fix optimizer software bugs and validate its performance before deploying on site.

The optimization solution was integrated with the chiller plant control system. A systematic and thorough testing and commissioning process was followed to bring the optimizer online.

Observations and later analysis showed that the optimizer's outputs were appropriate, as is expected for energy use minimizing actions.

After training the operators, site resource manager, and other site personnel, and providing the appropriate user manuals, the optimizer was handed over to site staff. Honeywell Laboratories in Minneapolis, MN, continued providing remote phone and onsite support for running the plant under optimizer control. The optimizer software was available and connected at the chiller plant from April 2015, to May 2016, and was enabled to operate the plant for some periods during that time. Data from the chiller plant is available for July 2015—May 2016. After removing invalid and shorter duration data, the data analysis shows the optimizer operated onsite for 39 days (24-hour [hr] periods) in several continuous periods. During the same period, the data shows 164 periods of original control days.

A rigorous baseline characterization methodology was developed to compare the actual energy consumption during optimization with the expected energy consumption under original control operation. Using all the data available, it was found that the optimized control of the plant did not reduce the energy consumption in the plant, and in most cases it is within one standard deviation error of the expected usage with original control. This unexpected result led to further analysis to diagnose the problems. The analysis showed a number of discrepancies in the input data to the optimizer software, which are explained in detail in the performance assessment section.

The optimizer works on real-time-sensed data to know the state of the plant, forecast loads, and calculate optimal operating commands. Poor quality or incorrect sensed data will not result in optimal outputs. The analysis of the data showed that there were no adverse effects to comfort conditions in buildings. The analysis also showed that equipment short-cycling, although more frequent than in original control, was still within guidelines provided by the site and able to be adjusted with user provided parameters. The effectiveness of the UI and the optimizer software architecture had mixed results.

IMPLEMENTATION ISSUES

Running the optimizer during the demonstration period depended on the chiller plant equipment being in good operating condition (e.g., not experiencing maintenance issues forcing manual operation) and the availability of site staff to monitor the operation periodically since optimizer-controlled operation is a large departure from current practice. Several troubleshooting periods took place in which the software was updated to manage site expectations and the difficult transition from Research and Development (R&D) to production prototype.

Failure to achieve energy and cost savings during the demonstration period stemmed from the following causes:

- incorrect inputs to the optimizer that were caused by communication disruptions or incorrect configuration changes;
- the complexity and prototype nature of the software required monitoring and support from skilled application engineers, but U.S. Department of Defense (DoD) site restrictions prevented remote access to the workstation;

- data-driven plant equipment models were potentially not well learned due to varied problems experienced by the optimizer preventing it from operating stably for longer periods with all equipment components;
- the transition of complex software from R&D to production prototype required the team to develop additional software tools and training of staff;
- the software's architecture and the implementation scheme to control the full plant from the supervisory layer caused two problems:
    1. potential network communication problems required development of additional optimizer software safety measures to prevent unsafe operation, and
    2. site staff were uncomfortable with a supervisory-level algorithm controlling lower level components in real time.

The results and lessons learned are planned to be published as part of a book (on intelligent control systems) as well as in a white paper.

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1.0 INTRODUCTION

1.1 BACKGROUND

Many of DoD fixed installations receive usable energy in the form of heating and cooling via central plants. These plants are excellent candidates for improvements in operational efficiencies because of their aggregation of energy production and distribution and their impact on the energy use profile of a military installation. Honeywell's predictive, automated optimization for central plants has significant potential to cost-effectively reduce energy consumption and costs by choosing the right operating points for all equipment, considering pricing and several other factors, in real time.

DoD central plants currently do not use automated optimization. Discussions with experienced central plant operators and energy managers about current operations make it clear that an opportunity exists for capturing efficiency savings from operational optimization. Central plants are currently operated to reliably meet all demands, and not necessarily for fuel economy or energy efficiency. Plant operators run the equipment according to a pre-set, fixed strategy. However, plant equipment efficiencies vary with load and external conditions such as ambient temperature. In addition, central plants have multiple chillers, boilers, and power generation equipment, which may differ from each other in capacities and performance curves. The ability to select the most efficient equipment for a load would offer great benefits.

The technology deployed is a model-predictive, run-time optimization technology to operate the generation, storage, and distribution of cooling and heating energy, while maintaining building comfort. Based on the inputs of upcoming loads, price signals, central plant performance models, and building response, a mixed-integer evolutionary optimizer algorithm solves the schedules and setpoints for the major and auxiliary equipment in the central plant. The central plant model is configured from a library containing the models of chillers, boilers, cooling towers, pumps, and a thermal storage system. A dynamic building model mathematically represents the changes in comfort conditions in the building in response to changes in energy supplied with the distributed chilled or hot water. The models are set up based on historical data and updated as new data become available. The optimal control commands are communicated to lower level controllers that operate the equipment in the central plant. Feedback from the buildings provides corrections to the long-term forecast load that are used to adjust the energy supplied.

This demonstration was designed to collect data about the original control and the optimized control, alternately. A software switch was incorporated in the optimizer, which enabled the optimizer to run the plant or switch to the original control operation. This ensured similar occupancy and functions for the buildings served by the central plants. All operational data including electricity and gas consumption from all equipment were collected in the optimizer's database for analysis.

1.2 OBJECTIVES OF THE DEMONSTRATION

The performance objectives of the demonstration were:

(1) Correct optimizer performance in simulation: objective met

(2) Optimizer software interconnection with plant control system: objective met

(3) 10% energy savings: objective not met

(4) Preserving comfort conditions in buildings: objective met

(5) Economic performance (net present value >=0): objective not met

(6) Low short cycling of equipment: objective met

(7) Effective user interface (UI) (qualitative): objective partially met.

1.3 REGULATORY DRIVERS

Executive Order (EO) 13514 (now replaced by EO 13693): EO 13514 set requirements for improving federal government efficiency by decreasing fossil fuel dependence. EO 13693 provides goals to maintain Federal leadership in sustainability and greenhouse gas (GHG) emissions reductions; specifically the goal to promote building energy conservation, efficiency and management by reducing building energy intensity by 2.5% annually through end of fiscal year (FY) 2025.

EO 13423: Section 2. (a) requires improved energy efficiency and reduced GHG emissions of the agency, through reduction of energy intensity by (i) 3% annually through the end of FY 2015, or (ii) 30% by the end of FY 2015, relative to the baseline of the agency's energy use in FY 2003.

DoD Policy: DoD's Strategic Sustainability Performance Plan [2] sets out DoD's priority to invest in reducing energy from traditional sources (Energy Management in Fixed Installations), sets a target to reduce Scope 1 and 2 GHG emissions by 34% between FY 2008 and FY 2020.

EO 13327: Section 3.b.ii. prioritizes actions to be taken to improve the operations and financial management of the agency's real property inventory.

2.0 TECHNOLOGY DESCRIPTION

2.1 TECHNOLOGY/METHODOLOGY OVERVIEW

The Central Plant Optimization for Waste Energy Reduction (CPOWER) central plant optimization solution, illustrated in Figure 1, provides optimal schedules and operating points for all equipment in the plant. It relies on equipment performance models, forecasted load, a building model, and energy price information. The equipment and building models are set up based on historical data and updated as new data become available. The optimization is based on minimizing energy costs or maximizing efficiency, and uses an evolutionary algorithm.

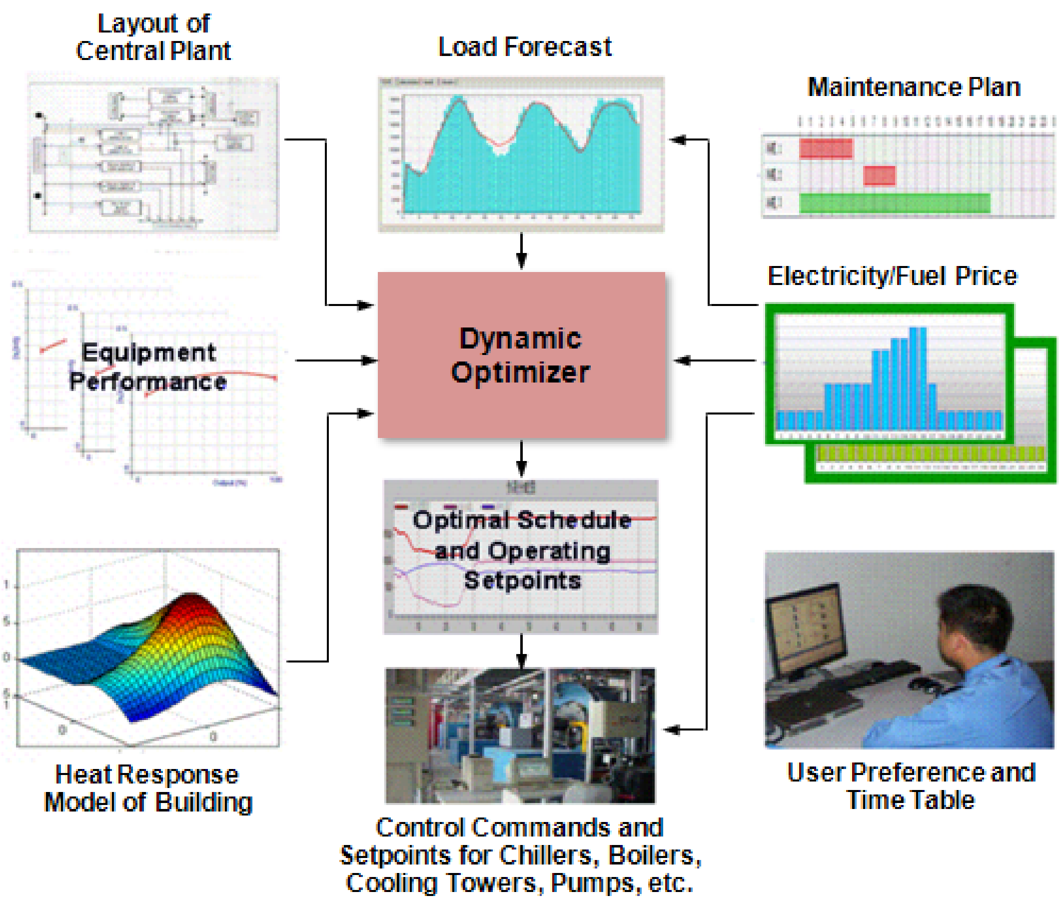

Figure 1. Technology Overview

2.1.1 Optimization Solution

The optimization solution in this project dynamically generates schedules and setpoints for plant equipment that minimize operating cost over a specific period. The solution concept is illustrated in Figure 1. The dynamic optimizer block shown in the center of the figure interacts with the equipment performance models, the specific central plant layout, building model, forecasted load, and external inputs such as electricity pricing. The optimal schedule and setpoints are communicated to the controllers.

The online information flow is conceptualized in Figure 2. A demand forecaster predicts loads for the next 24-hour (hr) period of optimization based on the current weather, load history data, and occupancy criteria. The central plant model is configured from a library containing the models of chillers, boilers, cooling towers, pumps, and thermal storage system. A dynamic building model mathematically represents the changes in comfort conditions in the building in response to changes in energy supplied with the distributed chilled or hot water. Based on the inputs of upcoming demand loads, central plant performance, and building response, the optimizer solves the schedules and setpoints for the major equipment in the supply and distribution of chilled and hot water. The optimal schedules and setpoints are used by the plant controller to operate the central plant. Feedback from the buildings provides corrections to the long-term forecast load that are used to adjust energy supplied and the setpoints.

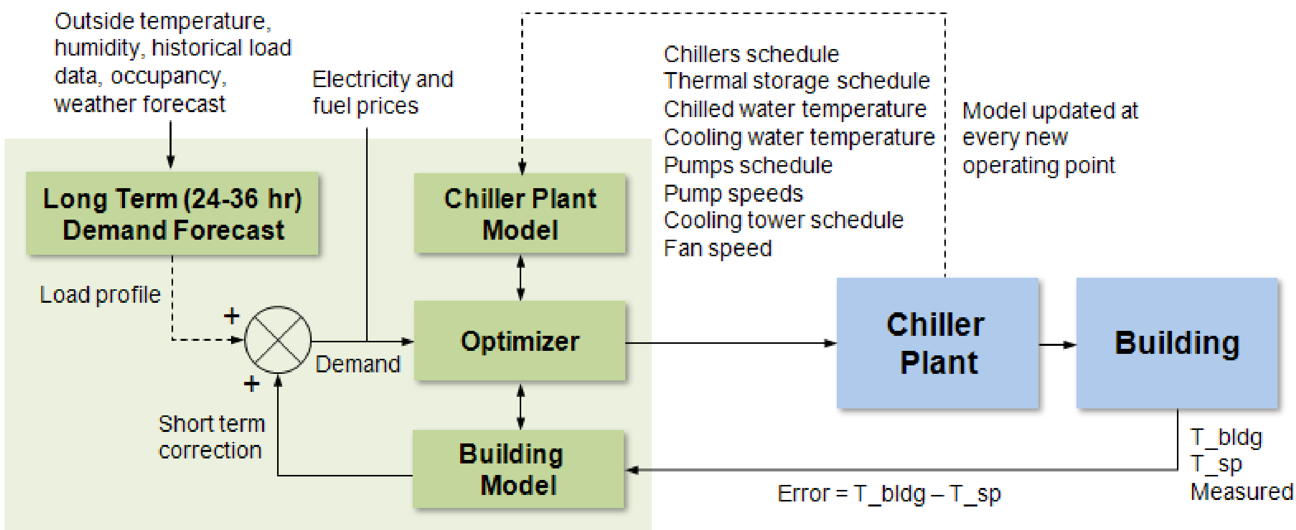

Figure 2. Optimization Implementation

2.1.2 Model Library

The model library is an integral part of the optimization solution that contains models to simulate the performance of the central plant and the building response under given conditions. These models are developed for a specific plant and building based on the data the optimizer collects when connected to the Building Energy Management System (BMS). Most of the models are either regression trees or a collection of regression trees. They are learned using historical data and are periodically updated. The solver can determine the optimal solution from various candidate solutions based on the plant performance. Since the optimizer models are based on data, they are continuously updated and, therefore, do not lose their efficacy when the equipment deteriorates. The models also provide the basis for performance monitoring of the plant. Separate models for each type of equipment are built based on regression tree principles and using several influencing factors as inputs, such as weather conditions, flow rates, and temperatures.

2.1.3 Problem Formulation and Solver

To search for the optimal schedule, the optimization problem is formulated with the following objective function and multiple constraints over an optimization horizon of h time steps:

$$Min\sum_{t=1}^{h}(Cost_t + \alpha Penalty_t)$$

subject to several constraints of equipment capacities, minimum outputs, ramp rates, interval between startup and shutdown, and others.

$Cost_t$ is the total energy cost of the central plant during the time interval t and is the sum of energy costs of all central plant equipment, determined from their models. $Penalty_t$ represents shortage of supply versus demand. α is a weight specified according to user preference for energy saving (α takes a bigger value) and comfort of occupants (α takes a smaller value).

The above optimization problem is further parametrized and solved to find an optimal solution for both discrete (i.e., ON/OFF) and continuous (i.e., setpoints) variables. This culmination of the modeling and optimization results in the entire system working in the most efficient manner.

2.1.4 Optimization Hierarchy

The optimization problem is solved in two levels: the energy source dispatch between the thermal energy storage and the chillers occurs first; the run-time optimization of the chillers, associated pumps, and cooling towers occurs in the next level.

2.1.5 Solution Architecture

Figure 3 shows the system architecture, illustrating the interaction of the optimization layer with respect to the central plant control system. Sensors and controllers are usually linked to Input/Output (I/O) modules to send and receive data in a uniform format through standard communication protocols such as LonWorks® or BACNet®. The data interface of the optimization module can communicate with these I/O modules, controllers, or building automation systems (BAS) using standard protocols. In the case of CPOWER at Ft. Bragg, the optimization software interfaces only with the existing BAS for ease of implementation and to standardize on one type of interface. The optimization module directly controls plant equipment.

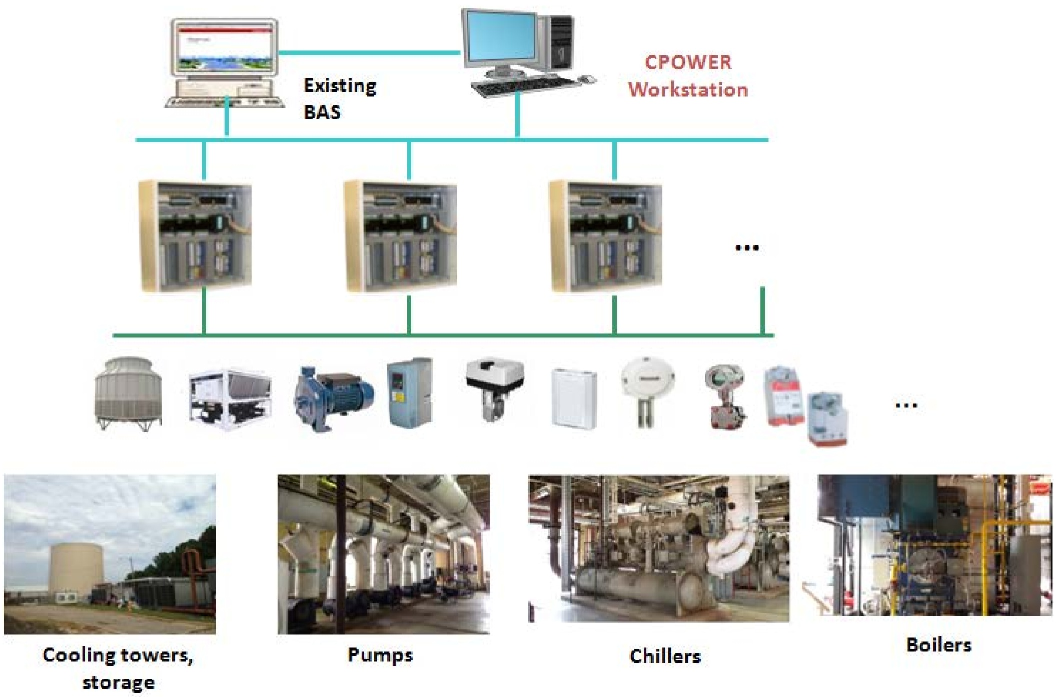

Figure 3. System Architecture

Figure 4 shows the software modules in CPOWER. The UI accepts user inputs and displays relevant information. A data interface reads data (temperature, flow rate, power, etc.) and sends control commands and settings (ON/OFF, temperature setpoint, pump speed, etc.) to all relevant devices. A database saves data that needs to be archived and shared. The model library contains simulation models of plant, building, and load forecast. The solver module solves for the optimum schedules and setpoints based on the problem formulated. The fault detector monitors for alarms or availability of chiller plant devices.

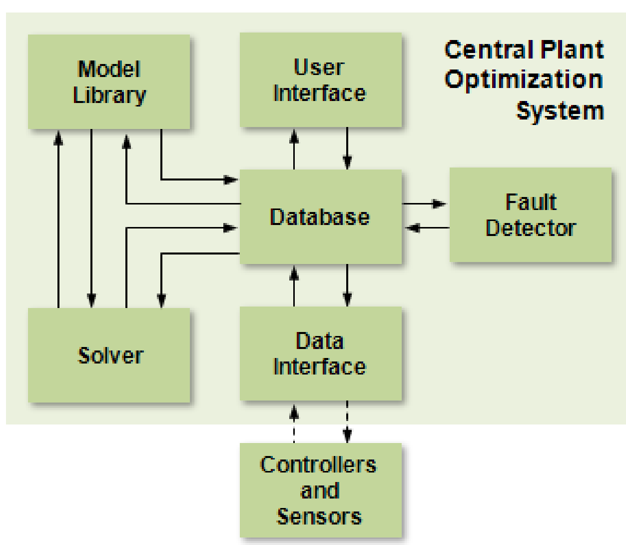

Figure 4. Central Plant Optimization Modules

2.1.6 Inputs and Outputs

System inputs can be categorized into five types:

1. Device Information
2. Connection Information
3. Ambient Conditions
4. Tariff Model
5. Running Settings

The outputs can be categorized as control commands, running settings, and supervisory information about the chiller plant. Major and typical items are described below.

2.1.7 Inputs

Device Information

The device information includes all basic properties of chiller plant devices (chiller, boiler, cooling tower, pump, etc.). Most of the design information is available from design documents or product specifications. Most of the running data can be read from sensors already installed to the chillers or the chiller plant.

Connection Information

The connection information describes how the water or piping system connects parts of a chiller plant together. Multiple connection matrices are employed to indicate which primary pumps can supply how much chilled water for a specified chiller, and which cooling water pumps can supply how much cooling water for a specified chiller or cooling tower.

Ambient Conditions

The ambient conditions include representative indoor and outdoor air temperature and humidity, which are averaged or given weighted averages from multiple sensors.

Tariff Data

The tariff data contains time-dependent price of electricity or fuel.

Running Settings

The system's running settings include maintenance schedule (when a specified chiller or pump will be offline in the near future for some maintenance work or overhaul), time settings of the chiller plant (e.g., when building working hours, which days are working days), temperature settings (the target indoor air temperature, allowed range of return/supply water temperature, etc.), and user preference for energy saving or human comfort.

2.1.8 Outputs

The number of outputs is relatively small. For a chiller, the control commands are Open/Close chilled water valve and cooling water valve (if applicable), chiller ON/OFF, and sometimes, the chiller working mode (cooling or heating); the running settings may include chilled water temperature setpoint.

For a boiler, the control commands are hot water valve Open/Close and boiler ON/OFF; the running setting is the hot water temperature setpoint. For a pump, the control command is ON/OFF and its running setting is mainly the flow rate, or if it is a variable speed pump, the frequency. Although the intelligent control system will monitor running status of the whole chiller plant, it will send commands or settings only to devices that the user chooses for system control.

The inputs and outputs specific to the plants in this demonstration are shown in Figure 8 and Figure 9 in Section 5.3 (Design and Layout of Technology Components).

2.1.9 Chronological Summary

The central plant optimizer is the result of several years of investment by Honeywell. No DoD funds were used in the development of the basic technology. Honeywell has been developing a suite of optimization and control technologies that target the energy supply, distribution, and demand. The first prototype was implemented at a Honeywell office building in Shanghai, China, in 2010. Several other prototypes of the solution were implemented in China between 2010 and 2013, including a hotel and office building (40,000 square meters), NanJing subway station chiller plant, and a chiller plant at an electronics manufacturing plant.

Summary of Development Under the Project

For the demonstration project, the optimizer was configured for specific conditions in the plants and developed the approaches and features for the thermal energy storage tank and the heat exchanger scheduling.

Heat Exchanger

The controls were developed in the software for automatically starting and stopping the heat exchanger, based on the site protocol.

Thermal Energy Storage Tank

Site-specific optimal operating strategies were developed for the chilled water storage tank.

Simulation Models for Testing

Simulation models of the central plants and building loads were developed as part of the project. The simulation models were used for testing the optimizer software prior to deployment to rectify operational issues, parameter configuration issues, and other unforeseen conditions.

Expected Application

The technology is deployable at all central plants across DoD sites. As an example, there are 13 central plants in Ft. Bragg and 6 in Ft. Jackson, which indicate enormous energy and cost savings potential. Information from Construction Engineering Research Laboratory (CERL) indicates that there are 155 heating plants in the Army installations alone. The number of cooling plants, combined heat and cooling (CHP), and heating plants at all DoD sites numbers in the hundreds. The optimization technology has the potential to be applied to much of these central plants.

Although it was demonstrated at a central plant, the optimization technology is applicable to chiller and boiler plants in buildings as well, and is therefore applicable to decentralized cooling and heating plants at DoD sites. However, because of the challenges a prototype faces in field installation, it is highly recommended that sites upgrade to the infrastructure and data capabilities needed by a data intensive application.

2.2 ADVANTAGES AND LIMITATIONS OF THE TECHNOLOGY/ METHODOLOGY

Advantages

The central plant optimization offers automated energy and cost savings without human intervention. It produces optimum operation outputs and directly supplies the control commands to the plant thus ensuring that the commands are followed.

With the automated optimization technology, the plant operational parameters are continuously calculated by using measured values; state-of-the-art alternatives use manufacturer-provided fixed specifications. For optimization over a time horizon, a long-term load prediction is used, and short term corrections are added for deviation from the forecast. This allows the operation to take advantage of the thermal storage effect of buildings. The optimizer also considers real time pricing for optimum scheduling; whereas for existing systems, the operational logic must be pre-determined for real time pricing levels for the day.

Limitations

If the plant is not well instrumented and automated, additional sensors and meters and communication must be added, which can increase the cost. Another limitation is that, if the optimizer is not properly configured, there is risk of equipment switching frequently to save energy, thus increasing maintenance costs. This limitation can be overcome by several means in the software. In the current version of the prototype software architecture, the optimizer also commands the sequence of low level control, which is not ideal for plant control. Delineating the optimizer and local control functions can overcome this limitation. The operational logic is not transparent to the operator, which can reduce acceptance, especially if the operator is not trained to understand it, which may lead to the optimizer not being used at all. The recommendation for future versions is to provide explanatory comments on the UI for optimizer actions.

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3.0 PERFORMANCE OBJECTIVES

Table 1 describes the project's performance objectives (PO) and summarizes the results.

Table 1. Performance Objectives

Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives			
PO1: Simulated Optimizer software performance			
Optimizer output of plant operating schedules and setpoints (various units)	Simulated (not site data) optimizer outputs of equipment schedules and setpoints	Optimizer outputs are within normal range of operation for equipment >95% of the time	The software performance met the objectives in simulation.
PO2: Optimizer software interconnection with control system			
Comparison of optimizer output and control system commands	Optimizer outputs and control commands for the same period	All required optimizer outputs are transmitted as control commands for plant operation.	The software interconnection objectives were met.
PO3: Energy savings			
Difference in plant energy consumption between baseline and demonstration periods in units of kilowatt hour (kWh) (cooling plant) and one million British Thermal Units (MMBtu) (heating plant)	Electricity and gas consumption at the central plants, prices, plant outputs, weather	>10% savings on weather normalized energy consumption data	The optimizer was commissioned successfully; however, post-data analysis revealed incorrect inputs into optimizer. Most of the demonstration period was consumed by troubleshooting configuration and control interconnections; hence energy savings were not achieved during the demonstration period.
PO4: Comfort conditions in buildings			
Deviation from minimum comfort criteria in representative buildings (degrees Farenheit)	Temperature and humidity data from representative buildings	Integral average error (IAE) from comfort conditions is within 10% of baseline period IAE.	The comfort conditions in buildings was not adversely affected during optimized operation and the objective was met.
PO5: Economic performance			
Simple payback or life-cycle cost metrics produced by the Building Life-Cycle Cost tool	Cost savings, initial investment cost, and annual maintenance cost of the technology	Net Present Value of >=0 for a 10 year project performance period	The main driver for cost savings is the energy savings (PO 3). As explained above, energy savings could not be demonstrated; therefore, the economic performance criteria were not met during the demonstration.

Table 1. Performance Objectives (Continued)

Metric	Data Requirements	Success Criteria	Results
Quantitative Performance Objectives continued			
PO6: Equipment short cycling			
Comparison of startup and shut-down frequency and duration between baseline and optimized operation for chillers and boilers	Equipment ON/OFF event data and times	ON/OFF frequency under optimized operation does not exceed manufacturer or operator specifications	Based on the analysis provided in Section 6.6, this performance objective has been met.
Qualitative Performance Objectives			
PO7: Effectiveness of UI			
Ability and comfort of operators to assess optimizer outputs for operating the plant to meet all loads	Feedback and questions from Directorate of Public Works (DPW) staff about the logic behind optimizer outputs, and actions taken	A skilled DPW energy manager can effectively use the interface and is comfortable with the optimizer outputs	The site resource manager was able to effectively use the interface and was quite comfortable with the software. Some end-users expressed concerns that will be considered in providing a better user experience in the future.

4.0 SITE DESCRIPTION

Fort Bragg, NC, was selected as the demonstration site. Within this site, the 82nd central cooling plant and CMA heating plant were used as the demonstration plants.

4.1 FACILITY/SITE LOCATION AND OPERATIONS

Demonstration Site Description: Ft. Bragg, NC, is one of the largest U.S. Army installations, served by six large central energy plants and a number of smaller plants. At Ft. Bragg, the 82nd Cooling Plant and the CMA Heating Plant were selected for the demonstration. The 82nd Cooling Plant consists of four large chillers (1000, 1200, 2000, and 2200 tons), four cooling towers, associated pumps, and a chilled water storage tank of 2.5 million gallons' capacity. This plant provides cooling to approximately 70 major buildings. The location of the plant is shown in Figure 5. The CMA Heating Plant contains three large natural-gas-fired hot water boilers, each having a heat input rating of 35 MMBH (million British thermal units per hour). Auxiliary equipment includes primary and secondary hot water pumps and air separation and water treatment equipment. This plant provides heating to approximately 100 major buildings.

The central chiller plant is monitored and controlled by Honeywell's Enterprise Building Integrator (EBI), and the heating plant is monitored by Honeywell EBI, but controlled manually at the plant using the boilers' Allen Bradley controls.

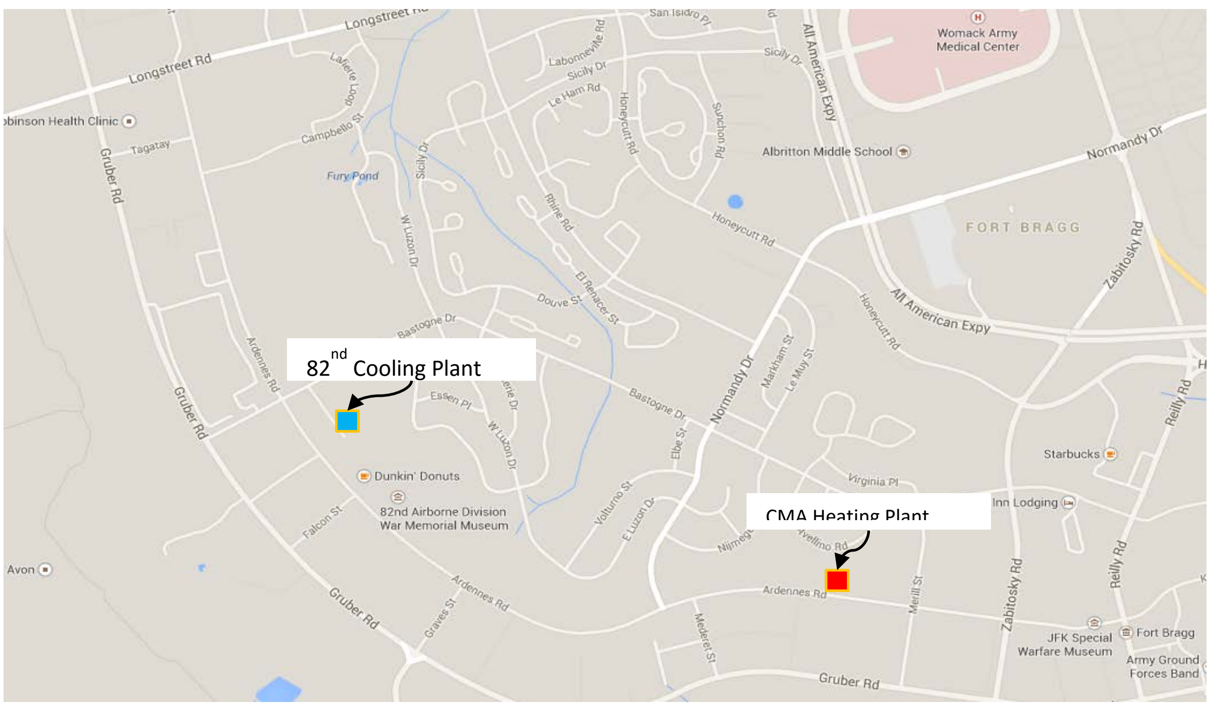

Figure 5. Location of Cooling and Heating Plants for the Demonstration

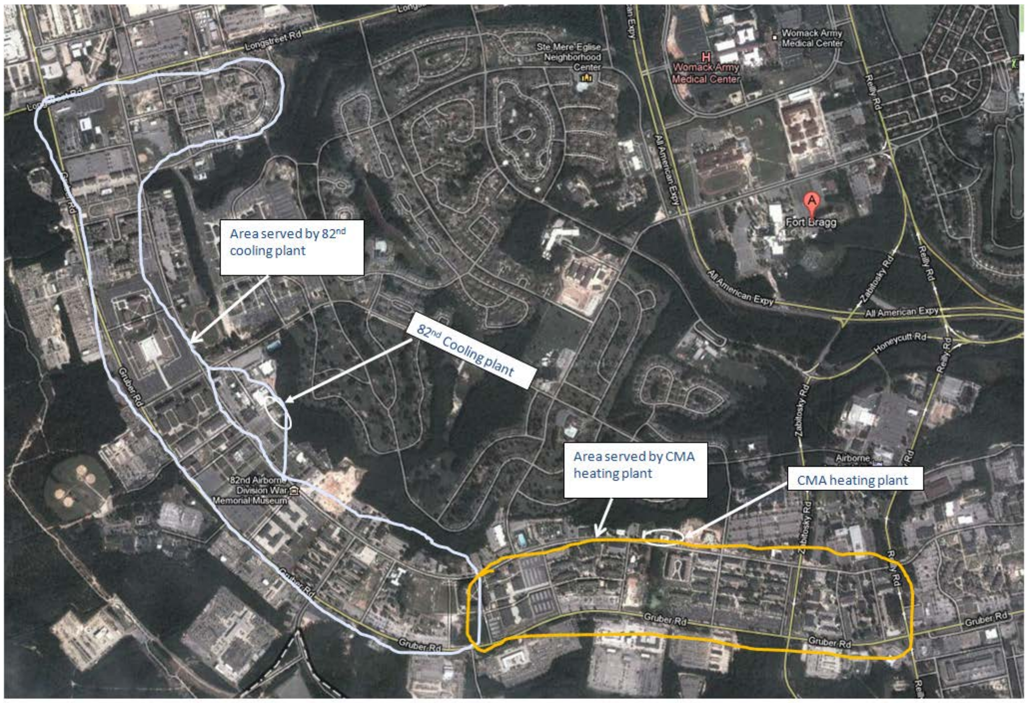

Figure 6. Location of Plants and Areas Served

4.2 FACILITY/SITE CONDITIONS

Plant Condition: Both the chiller and heating plants are overseen 24/7 by roving operators who care for several plants onsite. Figure 6 shows the location of the plants and the areas served. Honeywell's automation software EBI monitors both plants and has limited access to control the chiller plant. In the chiller plant, all control is automatic and has been programmed as different sequences by a skilled control technician. The operators have been trained to monitor the operator screens on EBI for this control. The control technician is also intimately involved with monitoring the plant or taking calls from the operators. The site was able to provide us access to all chiller plant controls including chiller starts and stops.

In the heating plant, the plant control—boiler start and stop and temperature setpoints—are all manual. The boilers have Allen Bradley controllers.

The site could not provide automated on/off or temperature control for the boilers because of warranty issues involving the boiler manufacturer (English Boiler) and the boiler control (Allen Bradley). This situation meant that the optimizer outputs were provided only as recommendations to the plant operators, who must then manually start or stop a boiler or change its supply temperature setpoint. In working with the plant manager, operators, and control technician, a process was developed so that the operators can follow the optimizer commands at the plant. Since there is a long start up and shutdown period (the boiler should be well warmed before turning on the gas to avoid thermal stress problems), the local control starts the primary pumps when commanded by the optimizer. The operator sees the primary pump operation (from anywhere on site, not just the specific plant) and is aware that the boiler should be turned on about 30 minutes after the pumps are on. The supply temperature change is gradual enough for the operator to make the change periodically at the plant.

5.0 TEST DESIGN

This section provides an overview of the system design and testing conducted during the demonstration.

5.1 CONCEPTUAL TEST DESIGN

Independent Variable	At the top level, the presence or absence of the CPOWER optimization software that operates the central plants
Dependent Variables	• Total electricity consumed by the selected central plants • Total gas consumed by the heating plant • Total cost of electricity for the selected central plants • Total cost of gas for the heating plant • Building temperature and humidity values (for occupant comfort) • Runtime of the central plant equipment
Controlled Variables	• Central plant heating/cooling equipment • Buildings being served by the central plant
Hypothesis	The hypothesis tested that the optimized operation reduces wasted energy and energy costs by smart allocation of loads, by considering real-time price signals, and by operating at the temperatures, flows, and pump/fan speeds to achieve maximum efficiency of the central plant energy system.
Test Design	The baseline period ran concurrent with the demonstration period at times that were convenient for the site personnel to monitor the optimizer operation and when the plant equipment and control were not down. A software switch was incorporated in the optimizer software and BAS that could switch the system between the original automatic controls and advanced optimization system. This switching could occur manually or at set intervals. Because of operator preference and constraints, the interval of optimized operation was for longer periods closer to a week. The original control was in control most of the time, interspersed with a few days of optimized operation. The data from the two operations was compared after applying weather normalization and day-of-week normalization for the operation with the existing control system (baseline) to enable fair comparison for dissimilar weather and occupancy schedules.

Test Phases	**Phase I: Control assessment, upgrades and data collection** This phase consisted of surveying the plants to assess the existing control and automation, upgrading the instrumentation and collecting plant specifications and data for the modeling task. Based on the assessment, the list of available points on the automation system is matched with the points needed for optimization. The instrumentation and communication is then upgraded to fill any unmet needs. **Phase II: Testing in simulation** The plant and load system are modeled in Simulink® with given plant layout and specifications. The model is tuned with the data collected in Phase I. The optimizer software was integrated with the model and tested in the simulation environment. **Phase III: Installation and commissioning** The CPOWER software was installed onsite and connected to the plant automation system (Honeywell EBI) by mapping point in the appropriate protocol. Commissioning tests will be performed and system brought on line to control the plant. **Phase IV: Data collection and analysis** After commissioning, the software switch enabled the plants to run with optimized control and the existing control. Data was collected during this phase and analyzed.

5.2 BASELINE CHARACTERIZATION

Because only the central plants' operation changed and no permanent hardware device was installed for this demonstration, the project test design enables a baseline characterization period that is concurrent with the demonstration period. The change between optimized control and original control is accomplished with a software switch within the optimizer-BAS system. The data for the baseline characterization was part of the optimizer database system, and was extracted and transformed for analysis in MATLAB®. Data were used from July 2015, to May 2016, along with data indicating original control operation.

The individual equipment power consumption data was summed at each time period to arrive at the total power consumed at the plant. The individual equipment included chillers, primary, secondary and condenser pumps and cooling tower fans. Other data used included: outdoor air temperature and humidity, indoor air temperature at representative buildings, type of day (weekday or weekend), and weather data such as wind speed. After analysis of the data, several anomalous spikes and constant power values were removed before using the data for modeling the baseline operation. Data was extracted for the baseline original control days using the 'EnableClosedLoopControl' point, which indicates if the plant was in optimized (value of 1) or original control (value 0). The dataset was divided into optimized and non-optimized periods; these periods were then sub-divided into 24-hr periods for energy analysis (after discarding any periods shorter than 24 hrs.). The total energy in KWh, average weather quantities, and indoor air temperatures for these 24-hr periods were calculated. The 24-hr period energy consumption is plotted against date in Figure 7.

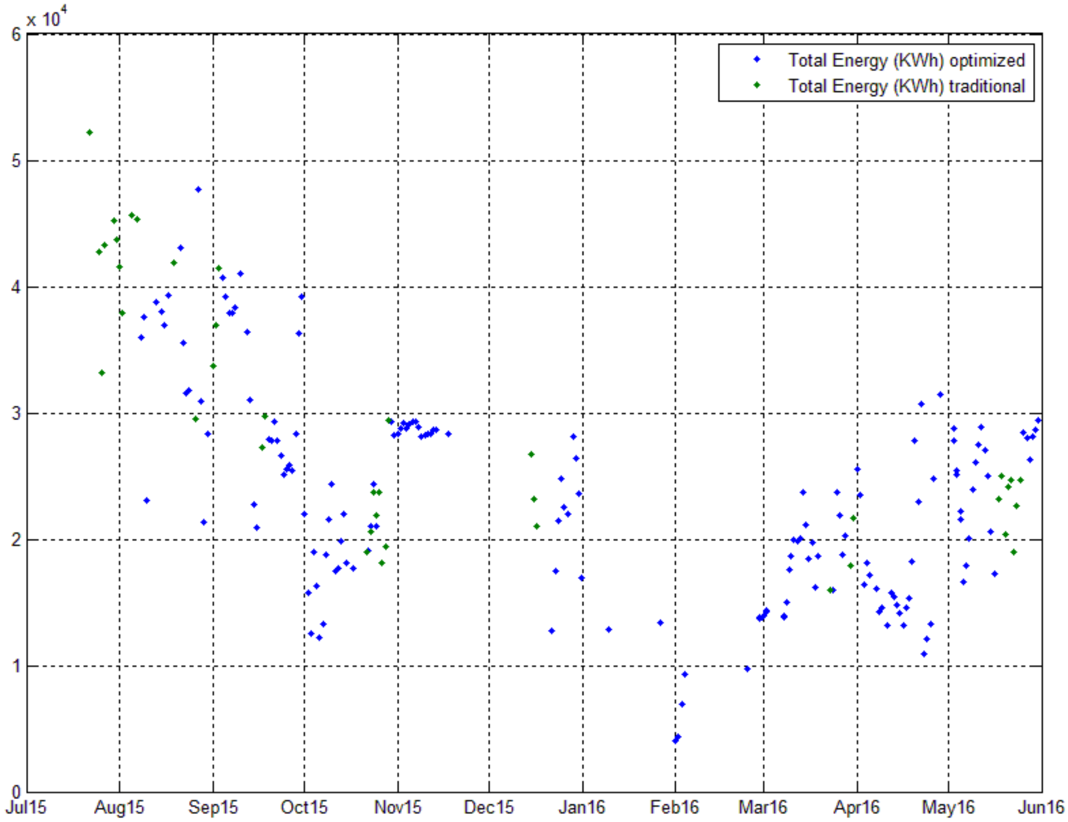

Figure 7. Energy Consumption (24-hr periods)

To provide a fair comparison, factors that affect the energy consumed need to be normalized. The approach was to develop a statistical model of the energy consumed during baseline operation, which can then be used to calculate predictions of energy usage for original operation at the conditions for optimized operation periods. The main factors affecting energy consumption are weather, indoor air temperatures, and occupancy. Outdoor air temperature, humidity (and wet bulb temperature as another measure of humidity), wind speed, heat index, averaged indoor temperature, and day type of weekend or weekday (in lieu of actual occupancy), were considered as factors in the regression models. The solar radiation data did not appear reliable in the weather dataset for the location, and hence it was not used. The energy consumption data has a lot of variability; to select a statistical model and regression variables that give the least prediction error, the model based on an evaluation of a combination of *regression model algorithm* and the *regression variables* was chosen. Baseline characterization was performed twice: first with available data from July to December 2015, and later with all data from July 2015, through May 2016, when all such data became available. Results for the full 2015–2016 dataset are presented. Table 2 shows the regression variables and regression models that were evaluated with the 2015–2016 data, using a 'leave-one-out' approach (explained below). Each set of regression variables was evaluated with each model type, for a total 24.

Table 2. Regression Models and Variables for All Data (July 2015 – May 2016)

	Model Type			
Regression Variables	**Linear**	**Interactions**	**Pure quadratic**	**Quadratic**
Nova OAT	X	X	X	X
Nova OAT + wetbulb	X	X	X	X
Nova OAT + humidity	X	X	X	X
Nova OAT + humidity + windspeed	X	X	X	X
Nova OAT + humidity + windspeed + weekday	X	X	X	X
Heat Index	X	X	X	X

Key

Regression variables:

Measured OAT: outdoor temperature measured on site
Novar OAT: outdoor temperature from external weather source (Honeywell Novar)
Humidity: Relative humidity from external weather source
Windspeed: Wind speed from external weather source
HeatIndex: HeatIndex from external weather source
Indoortemp: Averaged (4 buildings) measured indoor temperature
Weekday: Weekday or weekend day type

Regression models:

Linear: model contains an intercept and linear terms for each predictor.
Interactions: Model contains an intercept, linear terms, and all products of pairs of distinct predictors (no squared terms).
Purequadratic: Model contains an intercept, linear terms, and squared terms.
Quadratic: Model contains an intercept, linear terms, interactions, and squared terms.

Adding a weekday or weekend indicator or creating a separate weekday or weekend model did not increase the model accuracy in the 2015 data analysis, so this variable was left out of the evaluation.

Leave-one-out approach:

For each data set and each model type, leave one data row out of the training set and calculate the prediction error; compute the root mean squared error (RMSE) from each prediction error by leaving one row out at a time.

The RMSEs computed using the leave-one-out approach for *all data* using the models in Table 2 are shown in a color map representation in Figure 8. For this dataset and models, the quadratic model with outdoor temperature, humidity and wind speed as the regression variables provides the least RMSE. This model is used as the baseline energy consumption model for the chiller plant. Figure 9 shows the comparison between the actual and expected energy consumption for this model. As shown, even with the lowest RMSE model, the individual deviations are still significant.

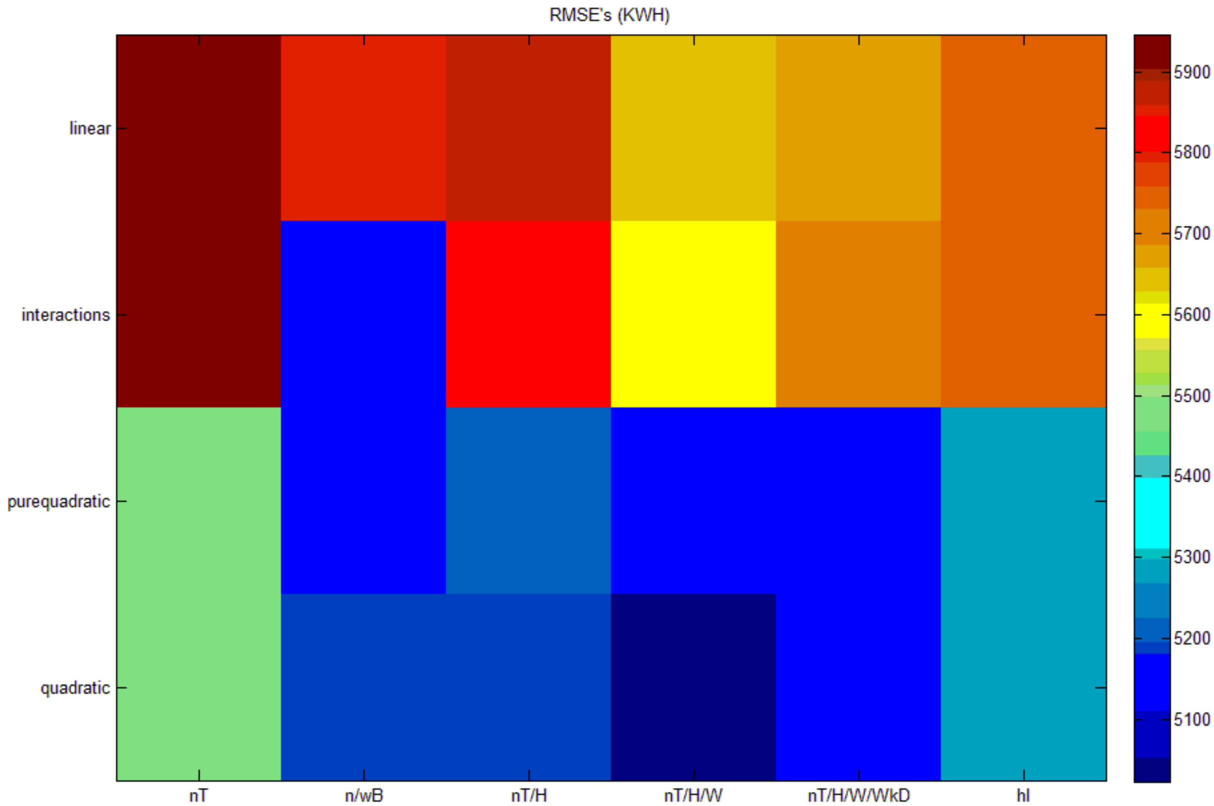

Figure 8. Evaluation of Models and Inputs (2015-16 data) – Color Map Representation of RMSEs

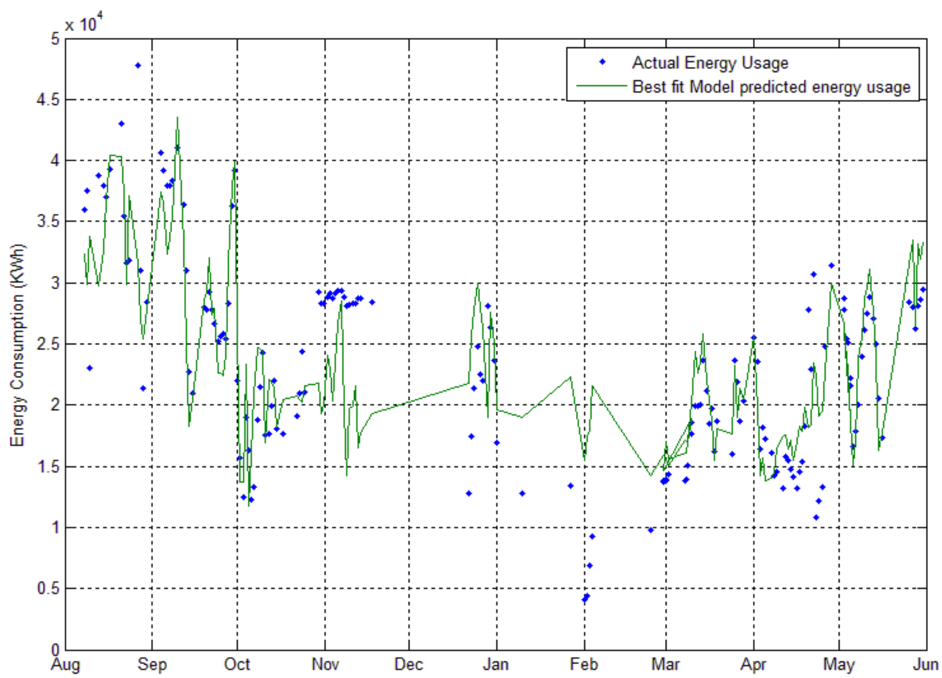

Figure 9. Actual and Model Comparison

5.3 DESIGN AND LAYOUT OF TECHNOLOGY COMPONENTS

The schematic in Figure 10 shows a chiller plant that is representative of the arrangement of the 82nd Cooling Plant at Ft. Bragg. A control system is usually installed to facilitate and simplify automatic control of the plant so that chillers, pumps, and cooling towers can be started or shut down automatically in a proper order, e.g., cooling water valve, cooling water pump, cooling fan, chilled water valve, primary pump, and chiller. The optimization solution dynamically generates optimal schedules and setpoints for plant equipment that will minimize overall operating cost over a specific time period. Figure 1, above, illustrates the functional components of the optimization system. The system architecture followed is the one shown in Figure 3 and the specific details are in Figure 11

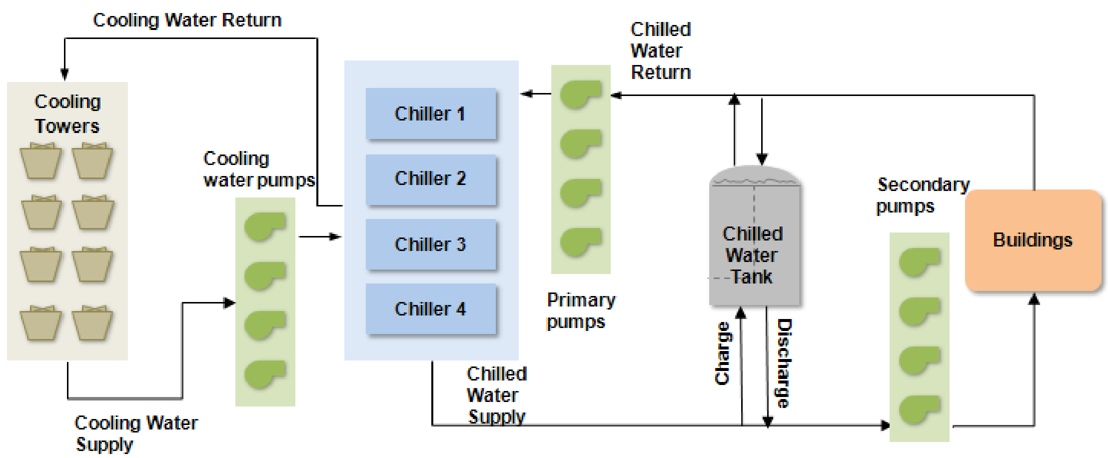

Figure 10. Chiller Plant Schematic

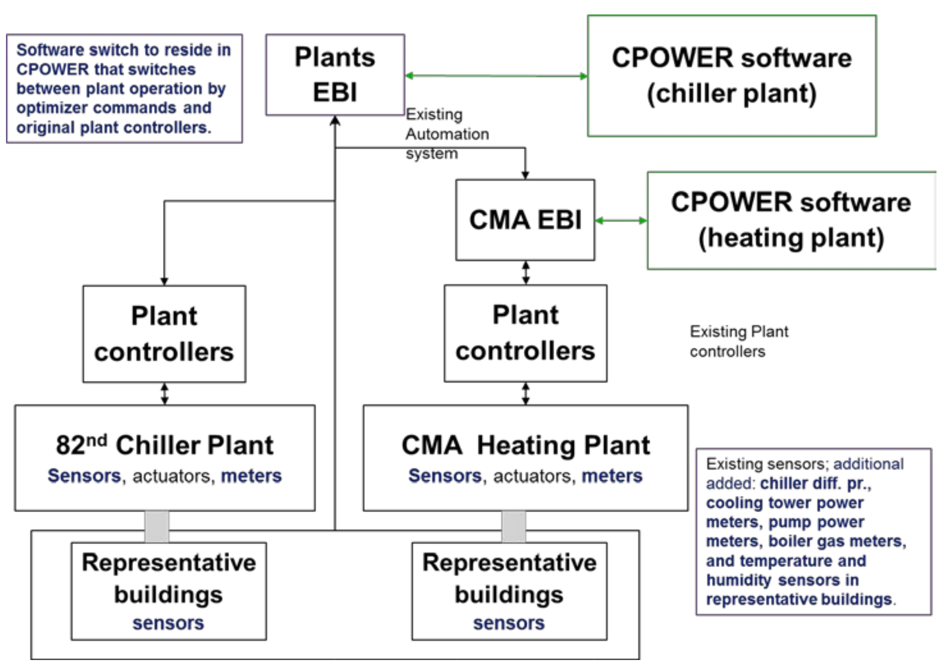

Figure 11. System Integration and Controls

5.4 OPERATIONAL TESTING

During commissioning, system communication testing, point-to-point control testing, whole system commissioning testing, and trial runs for performance were performed. During the demonstration period, performance testing was executed by running the optimizer for extended periods ranging from a day to a week. A chronology of all testing is shown in Table 3. The trial runs and performance tests overlap, since during most performance testing periods configuration or software issues were found that needed to be corrected. Nevertheless, because the project performance period has ended, results are being provided based on the analysis of these testing periods.

Table 3. Testing Chronology

Year -->	2015												2016							
Month -->	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8
Task 3: Site Implementation																				
Install with EBI and local controllers		H		C																
Testing																				
Task 4: Measurement and Verification																				
Post install monitoring and support																				
Data aggregation																				
Analysis and reporting																				
Periods of optimizer operation - Heating plant (days)		2	5	?	?															
Periods of optimizer operation - chiller plant (days)							7	6	4	8		7	?	?	?	?				
Site Issues - heating		X	X																	
Site issues - chiller					X	X	X	X	X	X	X	X	X							
	H	Heating Plant																		
	C	Chiller Plant																		
	X	Issues with site or with software adaptation to site																		

5.5 SAMPLING PROTOCOL

Data Description	Once commissioned, the software is set up to collect all control input and output data points along with additional derived quantities in its database at 1 minute intervals during optimized operation as well as during operation with the original control system. The Honeywell BAS also collects data from the plant at 15 min intervals, including data needed for energy savings calculations: energy consumption at the chiller and boiler plants, cooling or heating outputs, and weather.
Data Collector(s)	Honeywell staff onsite (Bruce Skubon, John Schlesinger)
Data Recording	Data recording was automatic, using the existing BAS (Honeywell EBI) and Distributed Control System (DCS); the newly added optimizer workstation connects to the BAS and records the data in its database.
Data Storage and Backup	The existing BAS and DCS have redundancy and data backup built into the system.

Data Collection Diagram	A system diagram provided in Figure 11.
Non-Standard Data	We obtained electricity price information separately for the demonstration period. This was input into the optimizer software, and recorded in the database.
Survey Questionnaires	No survey questionnaires were prepared or used.

5.6 SAMPLING RESULTS

Figure 12 is a summary plot of the raw heating plant data. It shows the supply, return temperatures, zone supply flow rate, total heating supply, and the gas used by the boilers. The 'Optimized' plot shows when the plant was under optimizer control and using operational recommendations provided to the plant. However, it is clear from this plot that the data for the original control (or non-optimized) period is not recorded, as seen by the constant value lines that correspond to the value at the end of optimizer controlled operation. This situation may have occurred either because the workstation was switched off between optimized controlled operation, or a duplicate set of points was created for the optimizer to read from and write to. The duplicate points were probably not written to the original local controller, which resulted in the optimizer not getting the correct I/O data. However, the varying supply temperature (Figure 13) indicates that the optimizer is working to command the hot water temperature setpoints for the boilers. In the original control, these temperatures are seldom changed from a fixed setpoint of 220 degrees F.

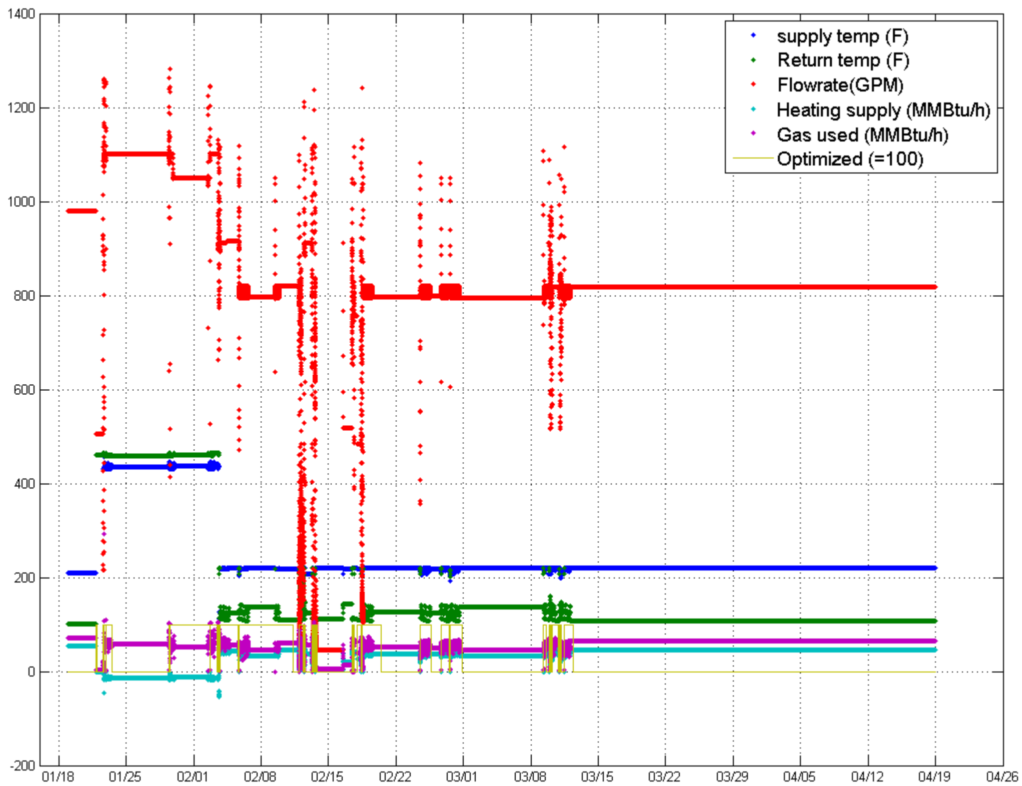

Figure 12. Heating Plant Operational Data

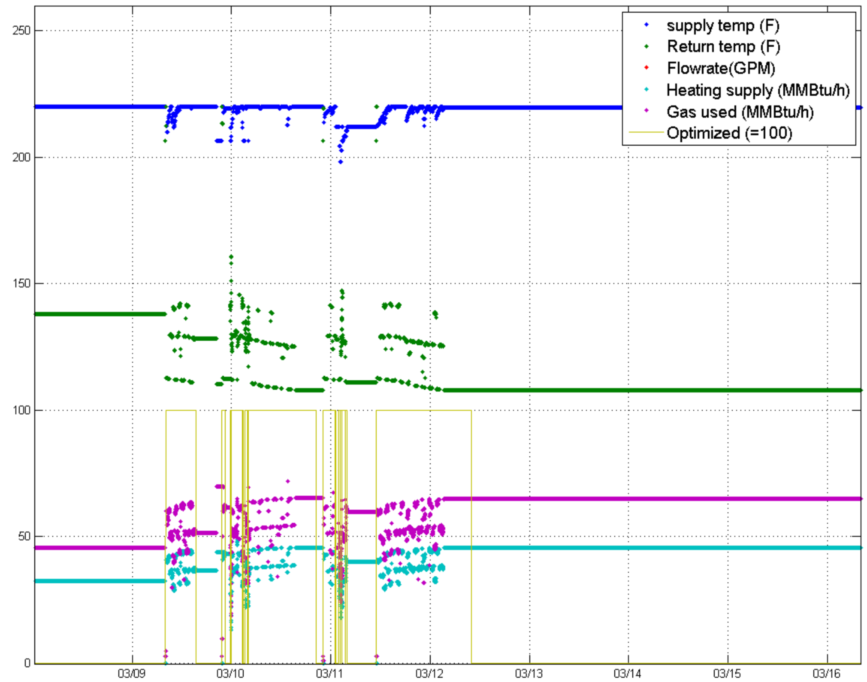

Figure 13. Supply Temperature Changing

Chiller Plant data:

The plots of optimized controlled periods, plant supply, and return temperatures and the total instantaneous power consumed during optimized and non-optimized periods are shown in Figure 14 - Figure 16.

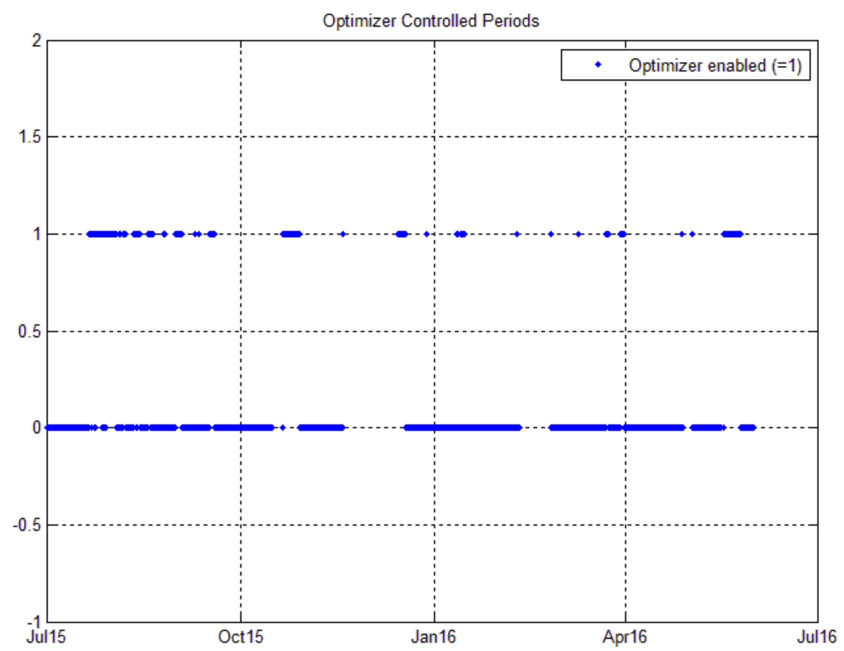

Figure 14. Chiller Plant Optimizer Enabled Periods

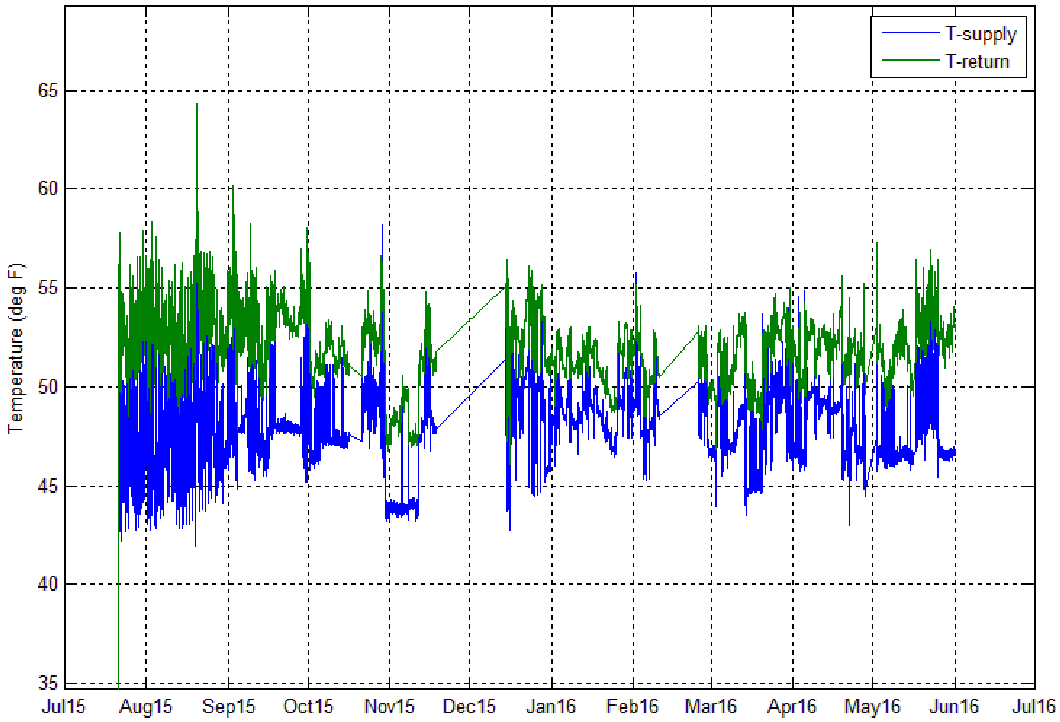

Figure 15. Chiller Plant Supply and Return Temperatures

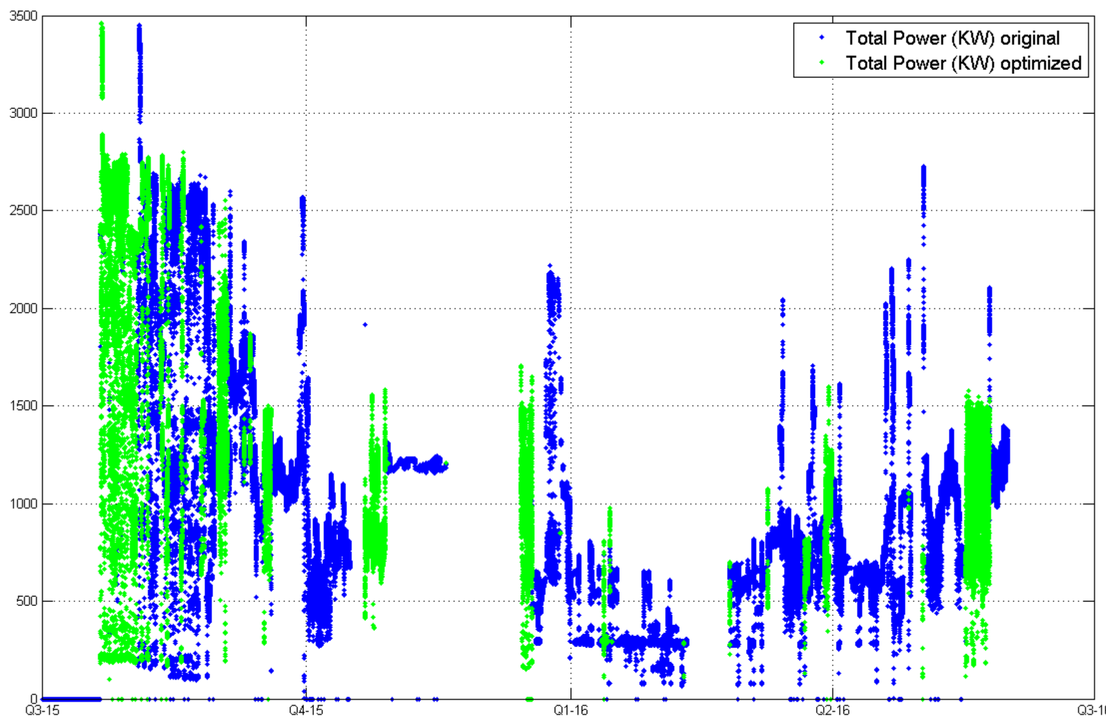

Figure 16. Total Power Consumed by the Chiller Plant

6.0 PERFORMANCE ASSESSMENT

PO1: SIMULATED OPTIMIZER SOFTWARE PERFORMANCE

The purpose of the objective was to show that the optimizer software can control the chiller and heating plants safely and within normal operating limits. The central plants and building loads were modeled in the Mathworks® Simulink environment. The optimizer software was interfaced with this model for testing. Several simulations of plant operation were performed and data was gathered to check safe and correct optimizer performance in simulation. Several combinations of activities were simulated covering the range of loads, weather and electricity prices, and their transitions in the simulation framework. The data collected (optimizer outputs) was compared graphically against known normal operating ranges for the equipment. Equipment run-times were compared with minimum prescribed in the optimizer UI. Performance objective PO1 was successful based on the analyses and metrics.

PO2: OPTIMIZER SOFTWARE INTERCONNECTION WITH CONTROL SYSTEM

The purpose of this performance objective was to test that the optimizer interface to the automation and control system works correctly, the inputs and outputs have been mapped correctly, and an overlooked local control doesn't override the optimizer. Several tests were performed during commissioning that included visual, quantitative and graphical analysis. With the successful commissioning of the optimizer, it is concluded that this performance objective has been met.

PO3 ENERGY SAVINGS AND PO5 ECONOMIC PERFORMANCE

The purpose of this performance objective was to measure energy savings in cooling and heating plants by operating them real time with CPOWER's optimization solution. The data recorded in the CPOWER database was used for analysis.

After commissioning, several issues were addressed to ensure that the optimizer ran as intended, the plant was operated safely and reliably, and the plant personnel were comfortable with the operation. The initial plan to switch the plant operation between the original control and optimizer control on alternate days or weeks was modified to operating with the optimizer for several days at a time, when site staff would be available to monitor, and no maintenance work was ongoing at the plant. All data for points that were mapped for CPOWER operation and other calculated data from the software were recorded in the CPOWER software database. MATLAB scripts read Microsoft Excel files exported from the database and organized them into user-friendly structures. Data extracts from different periods were merged to create .mat files with structures spanning the period from July 2015, through May 2016.

Most of the data analysis described below uses this data, except when other data sources were needed to corroborate or fill in gaps for periods of corrupted or unavailable data. Two other data sources were used for this: Weather data from an outside source (Honeywell Novar weather data) and the BAS EBI's data. Honeywell's Novar weather data is currently accessible from a Hortonworks cluster; we query this dataset to obtain csv files for the periods and place of interest. The plant EBI data is shipped as Excel file reports for each week, for several equipment points. A separate set of MATLAB scripts was created to read these data into a streamlined usable format.

Data preprocessing involved removing anomalous spikes, periods of constant measurement (indicating lost communication), and creating the scripts to demarcate optimized and non-optimized periods and create analysis windows of 24-hr periods within those periods to calculate total and average quantities. The total energy consumed in a 24-hr period during non-optimized periods were used to characterize baseline operation by building a regression model using several weather and occupancy factors. The baseline model was used to calculate predictions of total energy usage for original operation at the conditions for optimized operation periods. We compared the actual energy use during optimized periods with the expected energy use with original control. The results show that in most cases, the optimized actual consumption is within one standard deviation of the expected usage with baseline control. The unqualified overall usage however, does indicate that optimized operation did not improve the energy consumption and energy consumption increased by 5.84%.

Since the above results were completely unexpected, the data was analyzed to find out if the optimizer had been functioning correctly, if other factors were affecting optimized operation, and if input data into the optimizer during operation was correct.

1. Baseline model fit: Although a rigorous method was applied to model the baseline data, using several factors and model types, the best baseline model has significant deviations from the actual energy usage. It appears that several factors affect the total energy consumption of the chiller plant and additional data and additional factors (e.g., solar insolation) may be needed to obtain a better model.
2. Inputs to optimizer: During several periods of optimized operation the correct data was not being transmitted to the optimizer. Without a continuous presence onsite or a remote connection, it is impossible to know if the user provided parameters and real time inputs are correct while the optimizer is in operation. The optimizer software is complex and does not yet include standardized communication interfaces for controller or BAS integration, hence the application engineering skills to transfer the technology to the field have not been fully developed. The site staff includes mostly operations personnel. Software and communications must be monitored when in operation to ensure not just that the plant operates correctly (the site staff was qualified to do this), but the software is getting all its inputs and operating ideally (needed Honeywell Laboratories personnel or optimizer software experts for this). The indoor and outdoor temperature impacts how the optimizer forecasts load for starting and stopping chillers and calculated corrections to the supplied energy in the short term. The outdoor temperature had been wrong for certain periods. One of the first bits of anomalous data that was noticed with the new set of data in 2016 was the big spike in Total Power calculated from a summation of all equipment power data, which was traced to Condenser Pump #4. On being apprised of this power spike, the site staff lead immediately said that was probably why Chiller #4 was never being switched on, and would be switched off as soon as possible when the optimizer was in control: ‘the optimizer hated Chiller #4.’
3. Learning plant equipment models: The sequence of issues faced during the demonstration period meant that the optimizer software did not have long enough periods of stable operation for learning equipment models, and sometimes was not recording the correct inputs for the models.

The main driver for the cost savings comes from energy savings in this project. From the analysis provided for PO3 Energy Savings, it may be concluded that cost savings arising from energy savings could not be achieved during the demonstration.

PO4: COMFORT CONDITIONS IN BUILDINGS

The purpose of the objective was to ensure cooling and heating comfort is not adversely affected in the buildings during optimized operation. Space temperature data from representative buildings was collected during the baseline and demonstration periods. The analytical approach (1) compared the indoor temperature measurements with respect to the temperature limits specified in the optimizer, and (2) used the data collected in 2014 as baseline for comparison with the indoor temperatures during the demonstration period. Visual comparison of plots of baseline and optimized operation showed no significant adverse difference. Average value of indoor temperatures for cooling periods in 2014 (baseline control) was about 2 degrees higher than the average value during optimized operation. The results show the performance objective was achieved.

PO6: EQUIPMENT SHORT CYCLING

The purpose of this objective was to quantify short cycling of chillers and boilers. The plant equipment ON/OFF data from the database was used for analysis and computed ON and OFF time intervals for each chiller and boiler. The time intervals were compared with minimum ON and OFF times for such equipment as gathered from manufacturer specifications and operator interviews. The optimizer software allows the user to set up minimum and maximum run and rest times for chillers and other equipment. These parameters are soft constraints, since they may be overridden by other concerns such as safety or comfort. For example, the optimizer will respect a minimum run time setting of 2 hours, unless a safety concern such as exceeding maximum compressor current occurs, and then the chiller would be commanded OFF.

Quantitative information about the ON and OFF times for the four chillers are presented in Table 4 and Table 5. Columns 2 and 3 present the median duration of ON or OFF periods for optimizer and original control periods. The last two columns present the number of periods when the durations were shorter than the benchmark 2 hours (for ON), or 30 minutes (for OFF), versus the total number of periods in the demonstration period.

Table 4. ON Duration Statistics

Chiller	Median ON duration – optimization (minutes)	Median ON duration - original (minutes)	# Shorter than 2 hours /total # durations- optimization	# Shorter than 2 hrs/total # durations - original
# 1	169.5	217.5	22/108	11/62
# 2*	50	773.5	2/5	0/4
# 3	164	484	6/136	15/81
# 4	428.5	536	3/52	12/57

* Chiller # 2 had problems and was not run much during the demonstration period.

Table 5. OFF Duration Statistics

Chiller	Median OFF duration – optimization (minutes)	Median OFF duration - original (minutes)	# Shorter than 30 min/total # durations-optimization	# Shorter than 30 min/total # durations - original
# 1	73	565	0/107	1/63
# 2*	228.5	29245	1/4	0/5
# 3	45	376.5	14/135	5/82
# 4	141	401	1/52	1/57

* Chiller # 2 had problems and was not run much during the demonstration period.

On average, the chiller ON/OFF durations are shorter for the optimized than for original operation. However, that condition was expected, given the optimizer's objectives. During the demonstration period, the on and off times for both optimized and original control was analyzed. Apart from the larger number of shorter cycles, it is not clear that the optimizer is exceeding a threshold very frequently, even compared with the original control. The last two columns in Table 4 show that the original control also had several instances of cycle durations shorter than the benchmark above. Therefore, given that the optimizer software provides the flexibility to adjust the cycle times, we consider this performance objective has been met.

PO7: EFFECTIVENESS OF UI (QUALITATIVE)

The purpose of this objective was to evaluate the need to improve the operator UI for future widespread adoption. Feedback was obtained from interaction with the site staff during the commissioning process and demonstration. With frequent use, the site lead became familiar with the optimizer software and functionality compared to initial impressions. He was very comfortable putting the optimizer in control and letting it operate without supervision overnight and continuously over several days. The site lead liked that the optimizer changing the chilled water and hot water supply setpoints continuously, within specified limits, because the current control system is set up to operate at fixed setpoints.

The site personnel did not like the cycling of the equipment. The optimizer software was set up so that chillers, which are large equipment, did not switch frequently; however the pumps and fans were set up to give them flexibility in switching, within limits. The complexity and multitude of parameters to be set on the software can be overwhelming to plant managers and operators.

The plant personnel also did not know why the optimizer would make a particular choice when they would have intuitively made a different choice. The recommendation is to improve the software by providing a concise quantitative reason that shows the comparison of energy cost between a previous setting and current setting.

7.0 COST ASSESSMENT

7.1 COST MODEL

The costs given in Table 6 reflect an estimate based on experiences onsite and the vision for scaling the demonstration for commercial use. The estimate reflects considerations of software improvements to reduce site troubleshooting, changes in the software architecture, streamlined interface for optimizer with local controller or automation system, training of application engineers for installation.

Table 6. Cost Model

Cost Element	Data Tracked During the Demonstration	Estimated costs
Software license cost	Software license	\$60,000 - \$150,000
Software installation costs	Estimate of labor required to install and configure software	\$11,000
Training	Software Training to operators and technicians	\$6,800
Hardware and installation costs	Extra instrumentation on site – cost of hardware and installation labor	\$10,000
Cost of PC workstation	Cost of PC to host software	\$2,500
Maintenance	Software maintenance updates and customizations	\$15,200 (recurring)

Software license fees: This is the estimated cost of the software license for small- to large-sized complex chiller plants, ranging from 2 chillers and 1200 tons, to 5 chillers and 6500 tons.

Software installation cost: This cost includes labor to install and configure the software for a specific site by connecting to the input and output points. It includes the labor for installing appropriate compliant software on the workstation such as Army Gold Master OS and connecting to the automation system.

Operator training: This cost includes the labor cost for an application engineer to train the operators and facility manager.

Hardware and installation costs: It was assumed that a well-instrumented central plant would have automation, but that not all required measurements and actuation for optimizer software would be available. Typically, flow or BTU meters and power meters for pumps and cooling towers may not be available. In addition, it is possible that an existing sensor, actuator, or controller may have the requisite measurement but is not connected to the automation or control system. Communication cards may be needed to bring in all the points the optimizer requires. The installation costs include labor for installation of additional sensors, meter, communication cards, and the labor to map these measurement points to the automation system.

Cost of PC workstation: Cost of the computer to host the software on site. This estimate may change in the future as enhancements are addressed in the software architecture and automation system architecture, such as Cloud hosted services.

Maintenance: This estimate provides the labor cost of software upgrades and customizations for the site (after commissioning).

7.2 COST DRIVERS

Cost drivers that can affect the cost of implementing the technology include:

- Status of instrumentation and automation at the site: Several sensors and meters are needed to gather all data inputs for the optimizer. If a site is already well-instrumented and automated, the cost of upgrading to a supervisory level optimizer will be lower.

- Availability of skilled control technicians on site: The cost of implementation will decrease as more support and knowledge from the site becomes available on mapping and contextualizing control points.

7.3 COST ANALYSIS AND COMPARISON

The realistic cost estimates for the technology when implemented operationally are provided in the previous section (Table 6) and described further in the same section. Table 7 illustrates a cost analysis for a central chiller plant. The full comparative life cycle analysis and inputs are in Appendix of the full Final Report.

Assumptions:

1. For the cost analysis, it was assumed that a site with a large plant, but without the complexity of storage tank or free cooling that was encountered at the Ft. Bragg, NC site.

2. The site is well instrumented and the site has control technicians able to provide support for integrating the software at the plant.

3. The plant is well maintained, with minimum downtime of plant equipment.

4. The site has modern communication and automation infrastructure that is well maintained.

5. The optimization software has been productized with a robust architecture and other improvements, and application engineers and technicians trained in installation and commissioning provide standardized support.

Table 7. Summary Cost Analysis for a Chiller Plant

Inputs		Outputs	
Project Name:	CPOWER	**Results**	**15-yr**
Project Location:	North Carolina	Energy Consumption Cost Savings	$ 443,698.00
Analysis Type:	FEMP	PV of total savings	$ 215,698.00
Base Date:	April 1 2015	Net savings	$ 85,398.00
Beneficial Occupancy Date:	April 1 2015	Savings-to-investment ratio	1.66
Study Period (years):	15	Adjusted Internal Rate of Return	6.52%
Discount Rate:	3% (default	Payback period (simple and discour	7 years
Discounting Convention:	End-of-year	Electricity savings (kWh)	8,245,290.00
Electricity Savings Per Year (kWh)	549,761.29		
		Emissions reduction	
		CO2 reduction (kg)	9,761,923.21
Optimization Package Capital	$130,300	SO2 reduction (kg)	32,358.95
Annual Maintenance, Updates	$15,200	Nox reduction (kg)	14,606.06

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8.0 IMPLEMENTATION ISSUES

Three types of issues during the demonstration period were encountered:

1. **Technical and personnel resource issues:** The optimizer is complex software with advanced algorithms. In addition, it performs the actions of a simple controller, commanding equipment in real time. The optimizer needs to be integrated well with the existing automation, which requires experience and skill in a succession of staff in the project sequence—algorithm developer, software architect and developer, application engineer, control engineer and technician, BAS programmer, plant supervisor, plant operator, and site technical manager. A number of the issues occurred because the prototype software hadn't yet been architected for easy deployment, with appropriate tools, and this succession of staff weren't always available. A productized version of the software will not face the same issues and the mobilization of staff would be automatic: software that is a current business offering has the backing of trained staff to support the releases which is their job priority; a prototype version is still in the proof of concept phase and staff has to be mobilized on a case-by-case basis.

2. **End User concerns:** The end users were not always comfortable with the software. Some of the concerns have been documented in the performance objectives section. In summary, the main points of user concern are:

   a. Operating the plant with the optimizer is a very different from current practice. In current practice, the controller operates the chillers in different fixed modes; e.g., fixed chiller supply and condenser return temperatures. Under the optimizer operation, when the site staff see changing supply temperatures, flows, and switch on/off of equipment, they cannot understand the operation and motivation until they become more familiar with the software. To improve and speed up site staff familiarity with the software, one recommendation is to develop an improved UI that can explain automated system changes and the benefits to the user, real-time.

   b. The users felt that the optimizer cycled the equipment too much compared to the current practice. This concern was handled to some extent by configuring user parameters in the optimizer software as well as making changes in the software. This concern will have to be addressed through software improvements that can assign a cost to cycling, training of personnel, and data-driven explanations on the software front end to the user.

3. **Site issues:**

   a. **Data quality:** A lesson learned during this demonstration is that the data quality needs continuous monitoring. Although rigorous testing took place during commissioning and at other visits, the following two assumptions were incorrect because the focus was on correctly operating the optimizer: (1) that the data continues to be good if the optimizer can operate reasonably within limits, and (2) the data recorded by the optimizer is the same as that used by the local original control. From an operational perspective, it was found that despite bad data, the optimizer continued to function reasonably smoothly, however, it did not control optimally. It was discovered that a duplicate set of points were created for the interface to the optimizer, which meant that the optimizer did not see all the same states and commanded points that the original control used unless they were written to the duplicate points by the original control.

b. **Remote monitoring and troubleshooting:** Because of DoD site restrictions, no remote access to the optimizer workstation was permissible. This severely restricted the speed and quality of troubleshooting that could be provided without being on site. As stated previously, the software is complex and in a prototype state; therefore, it is difficult to manage and monitor continuously without the experts, since it works in real-time. The software should ideally be provided as a cloud service and, at a minimum, with expert remote support. Providing a process for secure remote access would have greatly increased the effectiveness and the value of the project.

c. **Information assurance:** A DoD-wide smooth information assurance process would have saved time and effort in this project. The information assurance pre-work was started in early 2014. It was understood from the DPW Energy Manager that the CoN (Certificate of Networthiness), and later the Interim Authority to Test (IATT), were the approval process for implementing a software onsite. The network architecture was created and gathering information on the process and information to be provided from the NEC as well as NETCOM through the DPW Energy Manager was attempted. CERL colleagues assisted in accessing the sites, as a Common Access Card was needed. This formal process was finally not required, since the software was implemented on a test basis, on a VLAN that is isolated from other site networks.

Procurement issues: All hardware required for implementation is standard commercial off-the-shelf [COTS] and not expected to be a concern in the future.

The program resulted in the successful commissioning of a very complex supervisory level optimization software that continuously receives real-time sensor data, computes optimal operating points, and commands plant equipment in real time. The testing provided valuable lessons for improvement of the software, user experience, and transitioning to DoD sites. Below are some recommendations for improvement of the specific technology process, as well as the project process.

(1) Re-architect the software to separate the supervisory and local control layers; the supervisory layer providing high-level operating schedules and setpoints which are then managed and controlled by the local control layer. This will not only improve the software ease of implementation and performance, but eliminate safety concerns due to network communication issues. It will also vastly improve the operational staff’s comfort with the software.

(2) Phase in the commercial transition with less complex plants, e.g., chillers only without additional energy sources.

(3) Develop standard implementation tools to quickly and reliably configure the software and connect it to the local control on site.

(4) Improve user experience by providing explanations for the optimizer’s major actions.

(5) Improve cycling frequency by considering equipment cycling as a cost in the optimization objective function.

(6) Data quality check process: Data quality checks were done at several points in the project, which led to successful commissioning. However, for any control, software or data-intensive applications that require continuous data streams, the data quality check and cleaning should be inserted as an automated data anomaly detection software. This would alert the field engineers if the data coming into the application is correct.

(7) For complex software that needs advanced development skills, it is difficult to develop software that is simple for field engineers to understand or that has no field engineer concerns. Securing remote access to the system would have made it possible for offsite expert engineers to monitor the in-operation performance and would have flagged issues early. Another approach may be to partner with advanced solution providers near the DoD site (e.g., universities, national labs or industry partners) who could be embedded onsite for closer monitoring of the system operation.

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APPENDIX A POINTS OF CONTACT

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